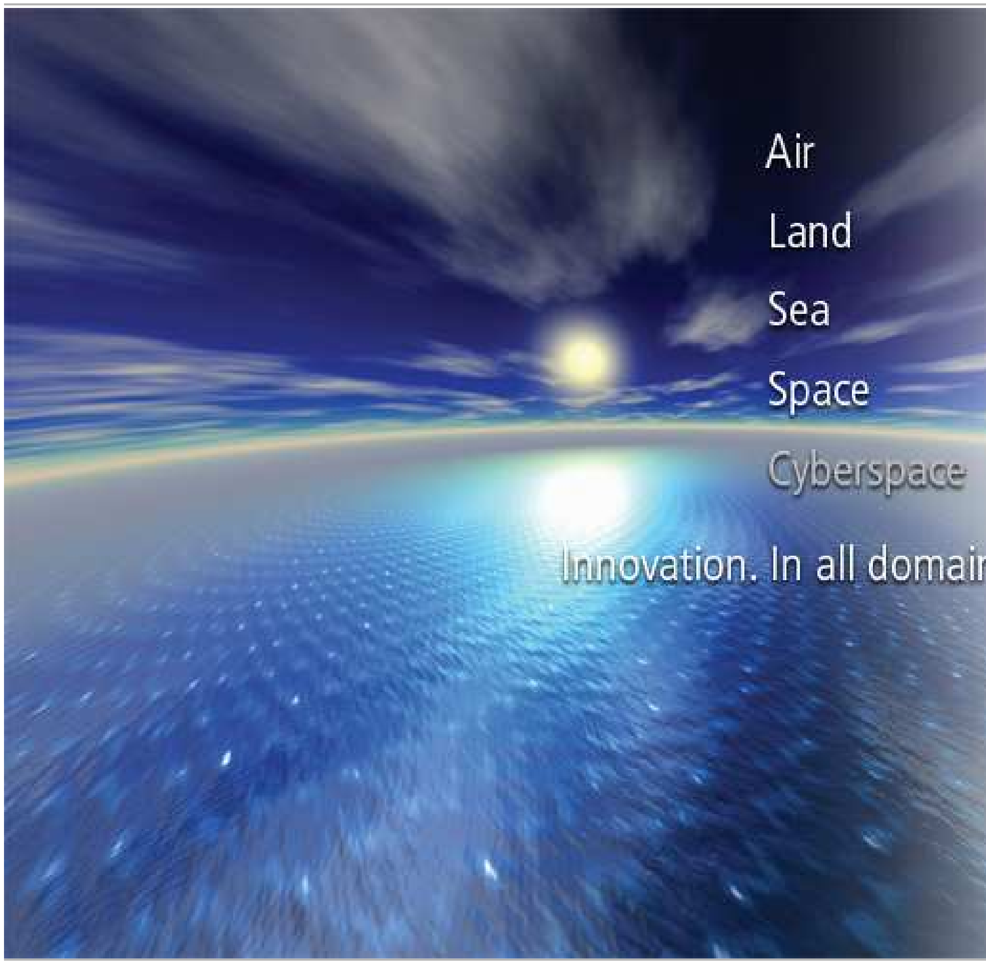


Raytheon
Space & Airborne Systems
Mirror Technology Needs

Mirror Technology
SBIR/STTR Workshop
June 4, 2010

M. David Makowski mdmakowski@raytheon.com
Matthew Jenkins Matthew_Jenkins@raytheon.com

Raytheon

Raytheon Government and Defense Business

Raytheon Company
Bill Swanson

Missile Systems	**Space and Airborne Systems**	**Integrated Defense Systems**	**Network Centric Systems**	**Intelligence & Information Systems**	**Raytheon Technical Services Co.**
Taylor Lawrence	Rick Yuse	Dan Smith	Colin Schottlaender	Lynn Dugle	John Harris

*›› **Core Markets: Sensing, C³I, Effects and Mission Support***

SPACE AND AIRBORNE SYSTEMS

Rick Yuse
President

2009 Net Sales: $4.6B
Employees: 12,400
HQ: El Segundo, CA

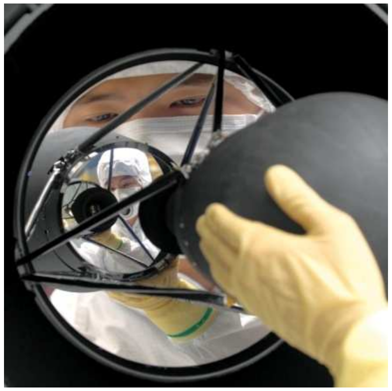
Leading provider of sensor systems for the network-centric battlefield

- Airborne radars and processors
- Electro-optic/infrared (EO/IR) sensors
- Electronic warfare and precision guidance systems
- Active electronically scanned array (AESA) radars
- Space and missile defense technology
- Intelligence, surveillance and reconnaissance (ISR) systems

›› Giving military forces the most accurate and timely actionable information available

Presenter's Perspective

- Not a technologist but rather one who sees/find applications for technologies
- Have been lucky enough to have developed some interesting technologies for emerging mission needs
  - 80's: Holographic gratings for high power wavefront sensing Nano-Radian vibration control
    HEL silicon cooled beamsplitter
  - 90's: All silicon carbide telescope for cryogenic application
    Bare Beryllium low scatter mirrors
    Vibration control for cryogenic space Telescopes
  - 00's: Low cost, producible structures for Space Telescopes
    Silicon Carbide Optics



Successful technology development is viewed in the context of a problem it solves or mission capability it provides

Raytheon

Technology Priorities

Related to Optics Technologies

DOD Priorities

- Defend the United States and support civil authorities at home
- Succeed in counterinsurgency, stability, and counterterrorism operations
- Build the security capacity of partner states
- Deter and defeat aggression in anti-access environments
- Prevent proliferation and counter weapons of mass destruction

- **Space**
  - Launch Detection
  - Space Situational Awareness
  - Rapid Replenishment (ORS)
  - Denied access ISR
- **Airborne**
  - Persistent Surveillance
  - IED Detection
  - Extended range target identification

Raytheon

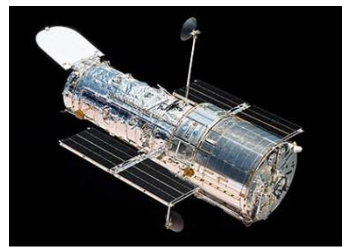
EO Mission Areas

Optical sensing missions have diverse technology needs

Space Domain

Weather & Environmental Monitoring

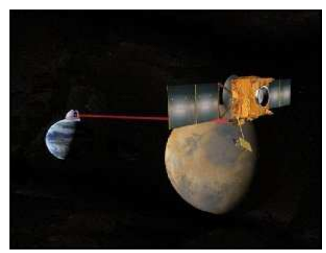
Intelligence, Surveillance & Recognizance



Astronomy

Missile Defense

Missile Guidance



Communications

Airborne Domain

Target ID & Tracking

Missile Defense (HEL)

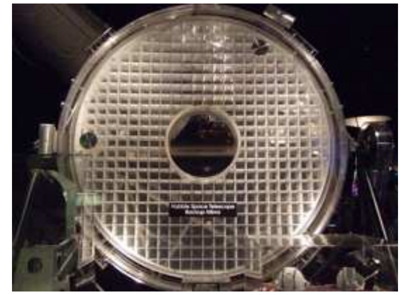
Intelligence, Surveillance & Recognizance

images courtesy of; NASA, USAF, Geoeye, space.com (all available on web)

Taxonomy of Mirror Characteristics

Sizes cm		Areal Density Kg/m²		Operating Temperature Kelvin	
Small	0-10	Very Low	<20	Very Low	<150
Medium	10-50	Low	20-75	Low	150-260
Large	50-180	Medium	75-200	Ambient	260-320
Very Large	> 180	High	>200	High	>320

Surface Figure RMS waves		Surface Roughness RMS angstroms		Coatings Bandwidth µm	
very good	<0.02	very good	<10	Narrow	< 0.1
good	0.02-0.05	good	10-20	Normal	0.4-1.0
relaxed	0.05-0.5	relaxed	10-50	Broad	1-3
High	> 0.5	High	>50	Very Broad	>3



The HST Primary Mirror backup on display at the Smithsonian Air & Space Museum, 180 Kg/m²

HST Wide Field Planetary Camera Mirror on display at the *Smithsonian Air & Space Museum, 80 Kg/m²*

Mirror characteristics grouped into ranges to simplify discussion of applications on next slides

Even within the same Optical system a range of mirror technologies may apply

Taxonomy of Missions and Mirrors

Type	Altitude	Sensor Characteristics	Mirror Characteristics							
			Sizes	Areal Density	Operating Temperature	Surface Figure	Roughness	Coatings	Cost	Fab Time
Space										
Astronomy	LEO	Broad Spectral Range, Multiple Instruments	Very Large	Very Low	Very Low	Very good to Very High	Very good to High	Very Broad	Very High	Very Long
Weather	LEO & GEO	Single Multi-Spectral Instruments	Medium	Medium	Low to Ambient	Relaxed	Good	Broad	High	Long
Missile Defense	LEO, HEO & GEO	Pan plus IR	Medium	Low to Medium	Very Low to Ambient	Relaxed	Very Good	Broad to Very Broad	High	Long
Missile Guidance	LEO	Single Band	Small to Medium	Low	Ambient	Relaxed	Good	Normal to Broad	Medium	Medium
ISR	LEO, HEO & GEO	Visible Pan or RGB	Large to Very Large	Very Low to Medium	Ambient	Good to High	Very Good to Relaxed	Normal to Broad	Very High	Long-Very Long
SSA/SP	LEO, HEO & GEO	Visible Pan	Small to Medium	Low to Medium	Ambient	Good	Good	Normal	Low	Short
Communications	LEO, HEO & GEO	NIR LASERs	Small	Medium to High	Ambient	Good to Relaxed	Good to Relaxed	Narrow	very Low	Short
Airborne										
ISR	high	Vis Pan plus IR	Medium	Medium	Ambient	Good	Good	Normal to Very Broad	Medium	Medium
Target ID & Tracking	low-medium	Vis Pan plus IR	Small to Medium	Medium to High	Ambient	Good to Relaxed	Good to Relaxed	Broad	Low	Low
HEL	medium-high	High Energy	Large	Medium	High to Very High	Good	Very Good	Narrow	Very High	Long

EO Mission areas need mirrors with different characteristics

Raytheon

Common Mirror Materials Properties

Discussion of the best material for a specific application must include cost & schedule

- Example: the best choice for a IR imager is likely Single Point Diamond Turned Aluminum even though its specific stiffness is relatively low

Property	Density	Modulus	Poisson's Ratio	Specific Stiffness	Thermal Diffusivity	Steady State Distortion	Transient Distortion	Unclad Surface Finish	Producibility Figure of Merit *
Material	Kg/m³	GPa	*higher*	Mpa-m³/Kg	10-6/m²/s	µm/W	s/m²-K	Å	low
	low	high		high	high	low	low	low	
Corning Fused Silica	2190	73	0.20	33	0.85	0.36	0.59	10	26
Corning ULE	2210	67	0.17	30	0.76	0.01	0.02	10	80
Schott Zerodur	2530	92	0.24	36	0.78	-0.06	-0.12	15	80
Brush Wellman I-70H	1850	287	0.25	155	60.8	0.05	0.19	25	312
Brush AlBeMet-162	2100	195.5	0.17	93	67.0	0.07	0.21	-	107
6061 Aluminum	2700	68	0.33	25	72.0	0.13	0.33	50	9
Single Crystal Silicon	2330	130	0.24	56	99.2	0.02	0.03	< 5	48
CVD Silicon Carbide	3210	460	0.17	143	116.2	0.01	0.02	< 5	168

* Producibility figure of merit product of relative cost, blank fabrication and polishing time. Shown for discussion purposes only

Your producibility mileage will vary

Convolving Missions with Materials

Type	Sensor Characteristics	Cost	Good Material Matches	
			Future Alternatives	Often used
Space				
Astronomy	Broad Spectral Range, Multiple Instruments	Very High	ULE, Zerodur Silicon Carbide	ULE, Zerodur, I-70H
Weather	Single Multi-Spectral Instruments	High	Silicon SIlicon Carbide	Fused Silica I-70H, Nickel on I-220H
Missile Defense	Pan plus IR	High	Silicon Carbide	Fused Silica Aluminum I-70H
Missile Guidance	Single Band	Medium	Beryllium	Fused Silica Aluminum I-70H
ISR	Visible Pan or RGB	Very High	ULE , Zerodur , Silicon Carbide	ULE, Zerodur
SSA/SP	Visible Pan	Low	Silicon, Fused Silica	Fused Silica, I-70H
Communications	NIR LASERs	very Low	Aluminum	Aluminum Fused Silica
Airborne				
ISR	Vis Pan plus IR	Medium	Beryllium Silicon Carbide	I-70H, Aluminum, Fused Silica
Target ID & Tracking	Vis Pan plus IR	Low	Aluminum	Aluminum, Nickel on I-220H
HEL	High Energy	Very High	Silicon, CVD SiC	ULE, I-70H, Moly

We will continue to use a range of materials in the future with ceramics like silicon and silicon carbide having an increased role

Raytheon

Technology Gaps

Type	Material Choice	Technology Needs
Space		
Astronomy	ULE, Zerodur Silicon Carbide	- Producibility of monolithic SiC parts up to 3 meters - segmented mirror systems 3 -20 meters
Weather	Silicon SIlicon Carbide	- Qualification if High performance Head mirror & mechanisms - Producibility of Silicon & SiC Telescopes for harsh thermal conditions
Missile Defense	Silicon Carbide	- Low temperature SiC Telescope suitable for gimbaled installation - SiC structural components
Missile Guidance	Beryllium	- Improved bare Beryllium cost and cycle times
ISR	ULE , Zerodur , Silicon Carbide	- Reduced ULE/Zerodur cycle time - Producibility of 1-3 meter SiC
SSA/SP	Silicon, Fused Silica	- within technology based - Producibility work to reduce cycle cost
Communications	Aluminum	- currently well served - technology may move away from reflective optics for this application
Airborne		
ISR	Beryllium Silicon Carbide	- Improved Beryllium producibility to increase production rates - integrated SiC sensor solution addressing SWaP vs. Performance
Target ID & Tracking	Aluminum	- currently well served - future capabilities may require Beryllium or SiC
HEL	Silicon, CVD SiC	- Productivity of 1-2 meter Silicon & SiC PM - Ability to integrate into an airborne Telescope

Technology focus needed on producibility of Optical Assemblies

Raytheon

Objective Cost Schedule Targets

- The table value represent aggressive cost & schedule goals for flight quality optics that generally support objective program schedules.
- Intended for general guidance and discussion only
- Tech development of a new material or process should include a plan to meet a target production rate and cost
- Some materials such as aluminum are capable of meeting these goals today but may not be candidates for specific application

		Non Recuring (1st unit)		Recuring	
Optic Size		Duration weeks	Cost $K	Duration weeks	Cost $K
Small	0-10	24	200	16	75
Medium	10-50	30	300	20	100
Large	50-100	36	600	24	300
	100-180	40	3,000	26	1,500
Very Large	> 180	70	10,000	48	4,000

Raytheon

Closing Comments

- Mission needs are generally not requiring significant performance growth in mirror materials
  - Exception is very large systems (JWST) where launch weight drives capabilities. Will need innovative solutions in addition to material improvements for continued growth.
- Material choice is often determined by schedule and cost
  - The lowest cost material, that meets a given need, is the best.
  - Many applications do not need “high performance” materials
  - New materials & process represent opportunities to reduce cost/schedule
- Program delivery schedules will continue to shorten
  - Economic pressure. Shorter programs cost less.
  - Need for new phenomenologies to combat global threats
  - Fast paced programs driven by desire for rapid replenishment (at low cost) will further compress timelines
    - TACSAT-3/ARTEMIS optics built in less than 6 months. This will become more common in the future.
- SBIR work has tended to focus on only a few mission areas but the technologies can benefit a wide range of applications

Some new materials do not progress out of the lab because they are not tied to a specific mission or program need.

Must have industry partner(s) in addition to government support.